MERGED RAINFALL FIELDS FOR CONTINUOUS SIMULATION MODELS

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ABSTRACT

Long sequences of rainfall at fine spatial and temporal details are increasingly required, not only for hydrological studies, but also to provide inputs for models of crop growth, land fills, tailing dams, land proposals for liquid waste and other environmentally-sensitive projects. Rainfall information derived from raingauges, radar or satellites may not individually be adequate to meet the detail required by hydrological models or other water resource studies. Therefore, a suitable technique is required to estimate rainfall values at a finer spatial and temporal resolution. Different techniques have been developed to merge rainfall information from raingauges, radar and satellites in order to obtain the "best" estimate of the "true" rainfall field. However, the length of the radar and satellite estimated rainfall records are currently limited. In this study, the mean areal merged rainfall, derived from raingauges and radar, was estimated for 26 subcatchments in the Leibenbergsvlei catchment for the period when radar data are available. By using the relationships derived between the merged rainfall and raingauge data, improved subcatchment rainfall may be estimated from the historical data from raingauges locating in and around of subcatchments. In most of the subcatchments the relationship between the mean areal merged rainfall of the subcatchment and the daily rainfall data from raingauges is strong (R^2 >=0.5). The relationship between the daily raingauges and mean areal merged rainfall of the subcatchments is used to adjust the historical rainfall data from the daily raingauges in order to estimate subcatchment rainfall for input to continuous simulation models.

Keywords: *Raingauges, Radar, Rainfall*, *Merged rainfall fields, Catchment rainfall*

1 Introduction

In the application of information derived from rainfall data in the fields of hydrology, engineering and agriculture, it is becoming increasingly important to know, or at least have a reasonable estimate of rainfall in space as well as time, and in more detail than it is possible to deduce from the data collected at raingauges in a sparse network (Pegram and Seed, 1998). Traditionally, mathematical interpolation techniques have been used to interpolate rainfall data from a raingauge network to estimate the rainfall at ungauged sites. However, a rainfield estimated using mathematical interpolation does not accurately represent the "true rainfall" field. Therefore, other techniques have been developed to improve the estimation of the spatial distribution of rainfall. Some of these methods generate synthetic rainfall values using statistical models (e.g. Pegram and Seed, 1998; Pegram and Clothier, 2001), or are models based on the physical properties of a rain cell or cloud (Gupta and Waymire, 1993), or are techniques that derive a sound link between the radar field and the raingauge data (Todini, 2001; Ehret 2002). Merged rainfall fields, derived from radar and rainguages, are currently the best estimate of the "true" rainfall field.

The reliable estimation of design floods provides safety in the design of hydraulic structure and risk assessment for water resource management. Design floods may be estimated from long records of observed streamflow data. However, the spatial distribution and record length of flow records are generally less than required for design flood estimation in most parts of the world, including South Africa. Design floods are frequently estimated from rainfall data using event-based approaches. Recently, continuous simulation models (CSM) have been successfully used to improve the reliability of design flood estimates (Cameron *et al*., 1999). Rainfall is the most important input into CSM and, therefore, CSM require the best estimate of rainfall, both in space and time.

Raingauges measure rainfall directly and rainfall depth accumulated over the period of interest is measured with a high degree of accuracy at points where the gauges are located. However, raingauge networks are too sparse to capture the spatial variability of rainfall (Wilson and Brandes, 1979). Radar, on the other hand, measures a volume-averaged returned signal power which is converted to rainfall in two steps: first to reflectivity factor (Z), and then to rainfall units (R). Although indirect, radar estimates of rainfall are continuous in space and provide information on the spatial variability of rainfall. However, rainfall estimated using radar lacks the accuracy at a point which raingauges provides (Wilson and Brandes, 1979).

Merging of radar and raingauge data using a merging technique enables the best estimate of the spatial distribution of rainfall to be made. However, the length of available radar records in South Africa is currently limited and most hydrological models require a long input sequence of rainfall records. Therefore, the objectives of the study reported in this paper are to validate and verify the merging technique developed by Sinclair (2004) and to develop a relationship between average daily rainfall depths for a subcatchment, estimated by the merging of radar and raingauge data, and rainfall measured by daily raingauges, which are selected to represent the rainfall in the subcatchment. This study was performed in the Liebenbergsvlei catchment where the required information was available.

2 Study Area

The Liebenbergsvlei catchment is a subcatchment of the Vaal River catchment and is located near Bethlehem in the Free State Province of South Africa, as shown in Figure 1. The Liebenbergsvlei catchment is in a relatively dry region of South Africa and has an area of 4694 km^2 which receives an average annual rainfall total of 650 mm (Pegram and Sinclair, 2002). Most of this precipitation falls during the summer season, which ranges from October to February. The mean annual runoff depth from the catchment for the twenty-one year period from 1978 up to and including 1998 was 38 mm (Midgley *et al.*, 1994). Rainfall has been intensively monitored in the Liebenbergsvlei catchment both by raingauges (daily and recording tipping buckets gauges) and by radar. Therefore, the Liebenbergsvlei catchment was selected a test site for this study.

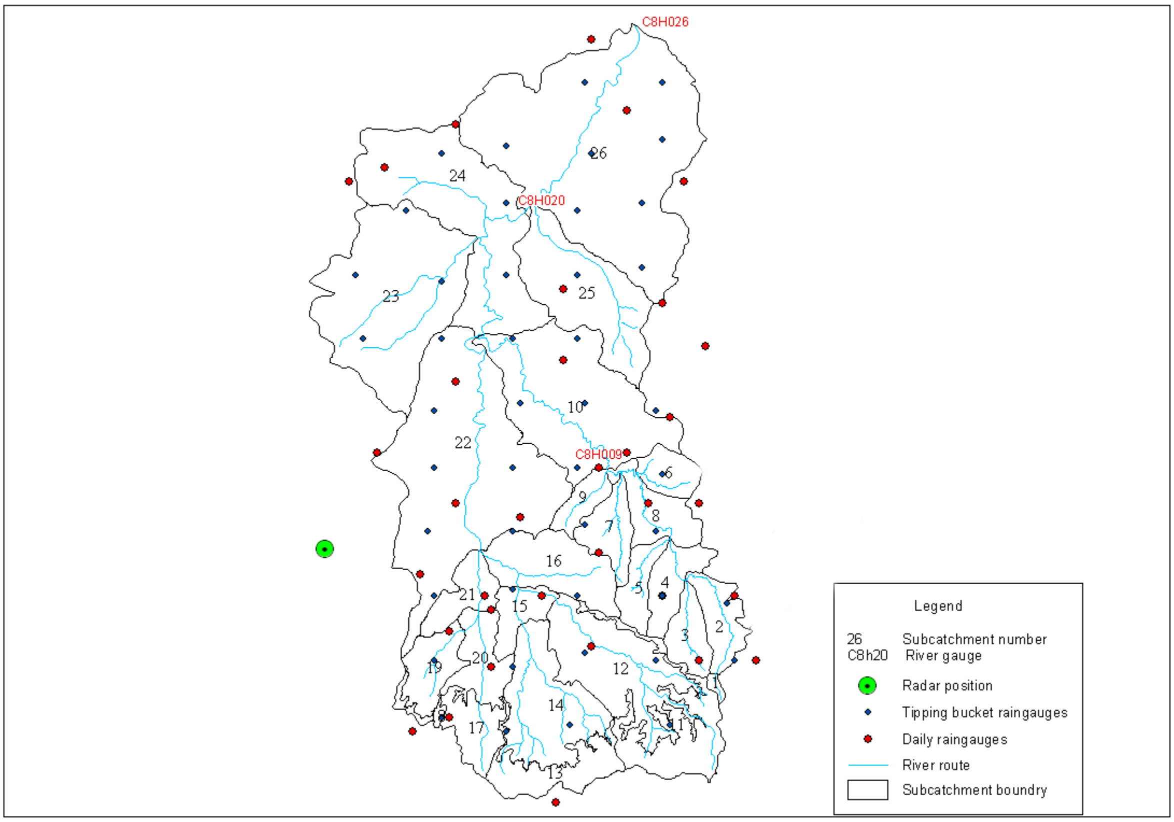

Figure 1: Location of raingauges and gauging weirs in the Liebenbergsvlei Catchment

3 Merged Rainfall Fields

The merging of rainfall values from raingauges and radar exploit the complementary characteristics of the techniques. Several methods have been developed for merging raingauge and radar data and the merged values have generally produced good results in terms of bias reduction, although little attention has been given to the reduction of variance (Todini, 2001). The different nature of the errors, which implies their independence (Seo and Krajewski, 1990), can be exploited to produce unbiased and more reliable estimates of rainfall. Following this idea, Todini (2001) proposed a Bayesian combination technique, based on the use of block Kriging and a Kalman filter, which seeks to eliminate the bias in meteorological radar estimates of precipitation and to produce precipitation estimates which have a minimum variance on pixels of variable sizes.

3.1 Conditional Merging

Radar produces an image of the unknown true rainfall field which is subject to several well-known sources of error (e.g, as detailed by Wilson & Brandes, 1979; Habib & Krajewski, 2002), but retains the general covariance structure of the true precipitation field. The information from the radar can be conditioned using the spatially limited information obtained by interpolating between raingauges to produce an estimate of the rainfall field that contains the correct spatial structure, while being constrained to the raingauge data. This process is illustrated in Figure 2. The conditional merging technique of Ehret (2002) makes use of ordinary kriging to derive information from the observed gauged rainfall data.

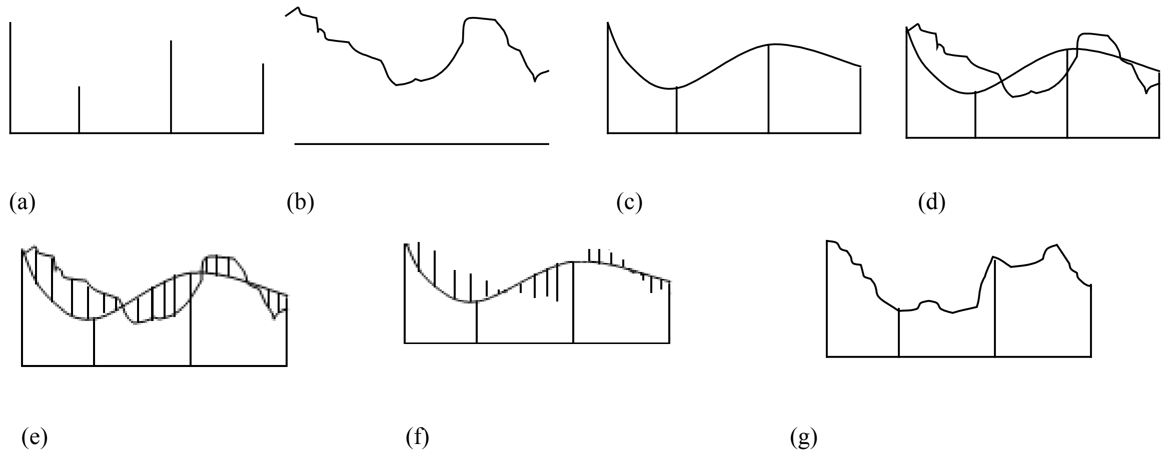

Figure 2 Conditional rainfall merging process (Pegram and Sinlcair, 2004)

With reference to Figure 2, the conditional merging process described by Pegram and Sinlcair (2004), and utilised in this study, is as follows:

(a) The rainfall field is observed at discrete points by raingauges.
(b) The rainfall field is also observed by radar on a regular, volume-integrated grid.
(c) Kriging of the raingauge observations is used to obtain the best linear unbiased estimate of rainfall on the radar grid.
(d) The radar pixel values at the raingauge locations are interpolated onto the radar grid using Kriging.
(e) At each grid point, the deviation between the observed and interpolated radar value is computed.
(f) The field of deviations obtained from (e) is applied to the interpolated rainfall field obtained from Kriging the raingauge observations.
(g) A rainfall field that follows the mean field of the interpolated raingauge data, while preserving the mean field deviations and the spatial structure of the radar field, is obtained.

3.2 Relationship between the Daily Rainfall Data and Merged Rainfall Data

Many hydrological studies require a long temporal sequence and spatially detailed and accurate rainfall data. However, the available rainfall data in South Africa are either long series of point rainfall, with no spatial information (raingauge rainfall data), or detailed spatial and temporal rainfall information, but with a limited period of record (radar and satellite rainfall values). Therefore, a relationship between the best estimate of the average daily rainfall depth in a subcatchment, obtained from merging the raingauge data with rainfall derived from a radar, and daily rainfall data from raingauges, is developed in this section.

The merging procedure was assessed in two stages. Firstly, the merging process developed by Sinclair (2004), which is based on the conditional merging technique proposed by Ehret (2002), was validated using rainfall data from the tipping bucket raingauges used in the conditioning of the radar rainfall values and, secondly, the merging procedure was verified using daily rainfall data from raingauges which were not used in the calibration of the merging process. Thereafter the reliability of the relationship between the averaged merged rainfall values for the subcatchments, obtained by combining the radar and raingauge data, and the raingauge data selected to represent the areal rainfall of the subcatchment, is investigated.

3.2.1 Validation of the Merging Process

In the merging process, Kriging of the raingauge observations is used to obtain the best unbiased estimate of rainfall on the radar pixels and the observed rainfall data, at the pixel where the raingauges are located, are fixed in the merged rainfall images without adjustment. Therefore, the average merged rainfall values at the same location as the conditioning raingauges, in this case the tipping bucket raingauges, should be equal to the measured rainfall at the conditioning gauge. At the pixels where the conditioning raingaugea are located, the merging algorithm has "exact" knowledge of the measured rainfall, and a 1:1 linear relationship (best fit straight line, $Y = x$; $R^2 = 1$) between the average merged and conditioning gauge values was expected. Anywhere else in the merged field it was expected that some error would be present between the true rainfall field and the merged estimate ($Y = ax + b$; $R^2 < 1$) at locations of raingauges not used during the merging process. However, the closer a raingauge is to a location of a raingauge used in the merging procedure, the more accurate the merged value was expected to be.

The validation was performed using all tipping bucket raingauges used in the merging procedure and all days where radar images were available to this study (2 October 1998 to 31 March 1999) are included in Figure 3, where a linear regression of $y = 0.937x \quad 0.2326 (R^2 = 0.9225)$ was obtained. According to the merging process developed Sinclair (2004), radar pixels with no rain are masked (i.e. excluded) and hence in regions where the radar registered no rain, the merged value is assigned zero rainfall, even though a raingauge in the region may have registered rainfall. This is a trade-off between being wrong at the raingauge in a few cases and having rainfall over the entire data domain which means many "false rainfalls" elsewhere in

the region of interest (Sinclair, 2004). When the merged values with masked zero values, resulting from no rain registered by the radar, are removed from the relationship, a near perfect regression relationship of $y = 1.001x \quad 0.036$ ($R^2 = 0.9996$) was obtained, as shown in Figure 4.

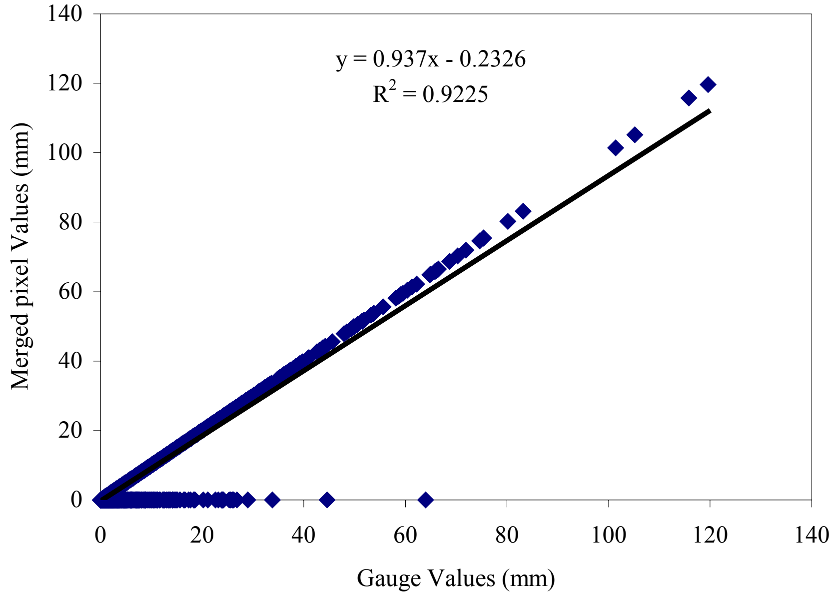

Figure 3 Validation of the merging process for all tipping bucket raingauges data

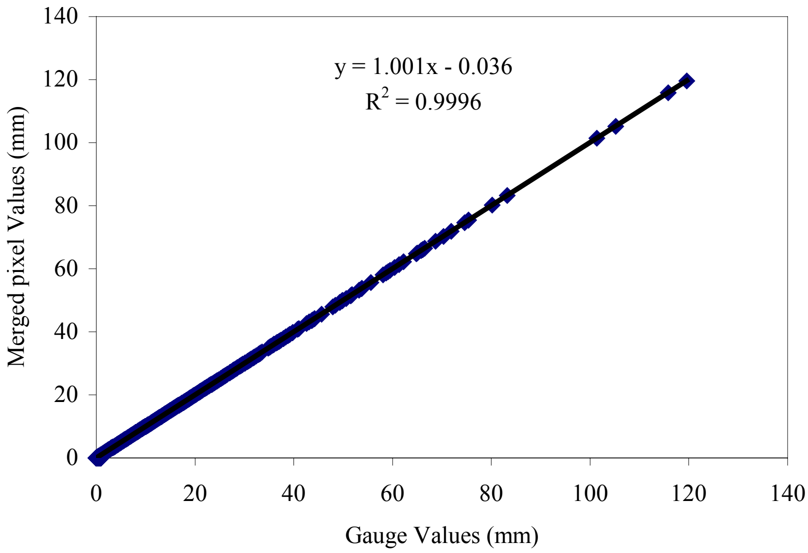

Figure 4 Validation of the merging process for all tipping bucket raingauge data after merged zero rainfall values resulting from no rainfall in the radar images were removed

From the validation of the merged rainfall with the tipping bucket raingauges used in the conditioning of the radar images, it is evident that the merging procedure developed by Pegram and Sinclair (2004) successfully assigns rainfall values to the merged pixels from the respective raingauge values used in the conditioning of the radar images.

3.2.2 Verification of the Merging Process at Raingauges not Used in the Conditioning of Radar Images

Average merged pixel values at daily raingauges, which were not used in the conditioning of the radar pixel, were compared to the gauged values. Raingauge 0331607W, located in Subcatchment 22 as shown in Figure 5, is used as an example of the verification, where a relationship of $y = 1.0385x - 0.0675$ $(R^2 = 0.7018)$ was obtained from the comparison of rainfall from the daily raingauge and the merged pixel values at the raingauge location (Figure 6). However, as explained above, some of the merged pixels are assigned zero values at pixels where the radar registered no rainfall and when these pixel values are removed from the analysis, the relationship improves to $y = 1.1814x + 0.1224$ $(R^2 = 0.8205)$, as shown in Figure 7.

Figure 8 shows the relationship between tipping bucket Raingauge L015, used in the conditioning of the radar rainfall images, and the average merged pixel rainfall values at the location of Raingauge 0331607W. The relationship between the point rainfall from the daily raingauge, not used in conditioning of the radar rainfall images, and the average merged rainfall values of a pixel at the location of the daily raingauge, is a function of the radar rainfall values, the point rainfall from the conditioning tipping bucket raingauges which are close to the daily raingauges, and the distance between the tipping bucket raingauges and daily raingauge. Therefore, Figure 9 shows the characteristic rainfall pattern between the point rainfall from the tipping bucket raingauge and average merged rainfall values and it demonstrates the influence of the tipping bucket Raingauge L015 on the relationship between the point rainfall from daily raingauges and averaged merged rainfall values of pixels at the location of the daily raingauges.

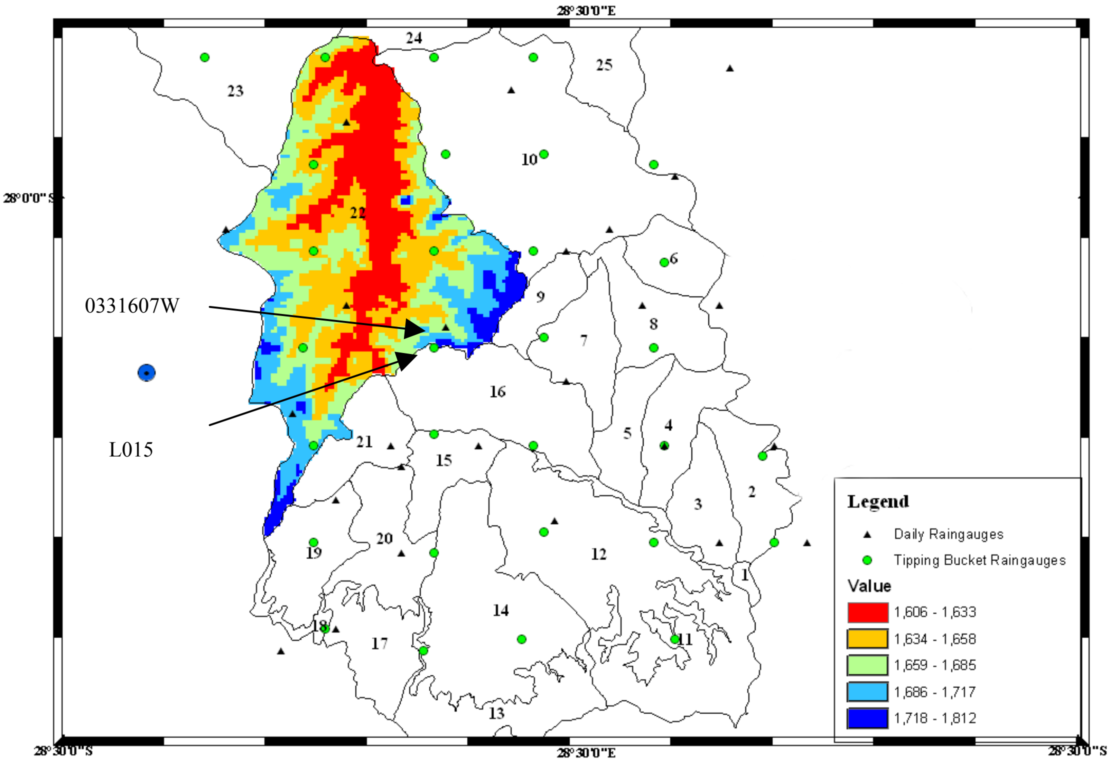

Figure 5 Location of Raingauge 0331607W and altitude distribution in Subcatchment 22

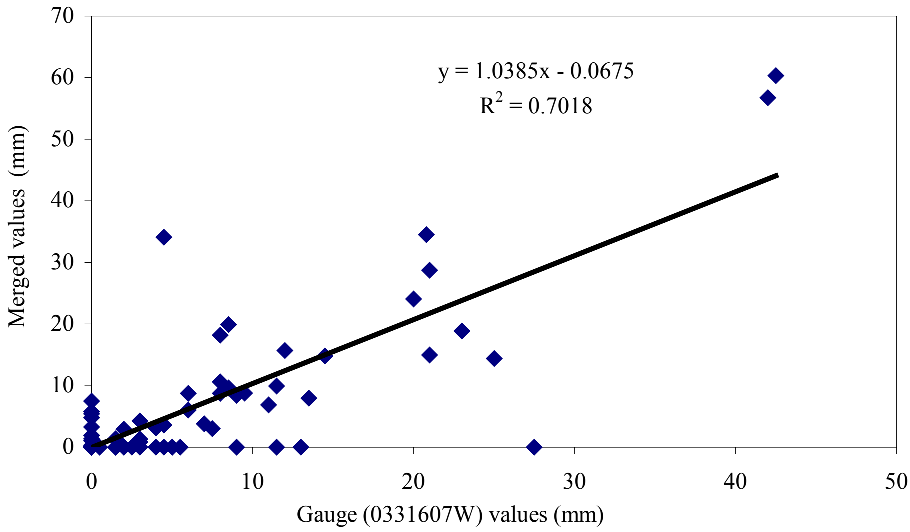

Figure 6 Comparison of daily rainfall from Raingauge 03312607W, which was not used in the conditioning of radar rainfall values, and merged pixel rainfall values at the raingauge location

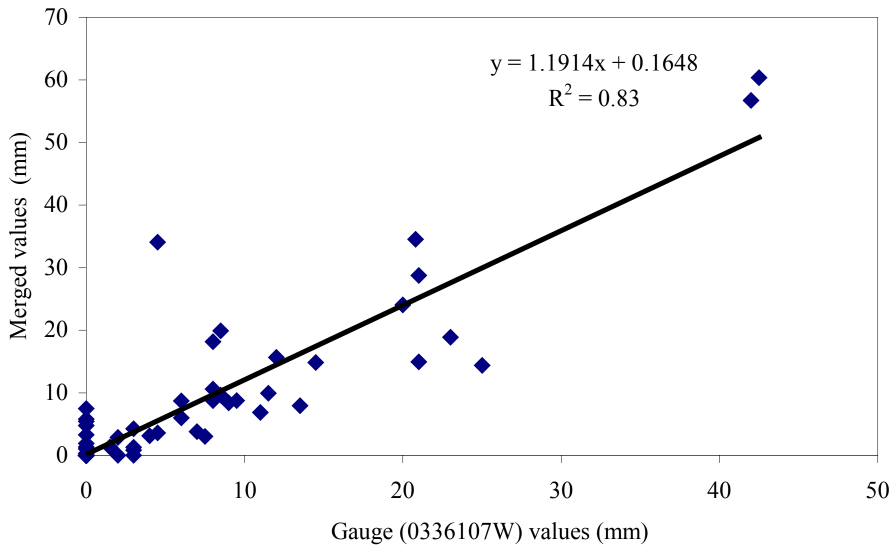

Figure 7 Comparison of daily rainfall data from Raingauge 03312607W, which was not used in the conditioning of radar rainfall values, and merged pixel rainfall values at the raingauge location after merged zero rainfall values resulting from no rainfall in the radar images were removed

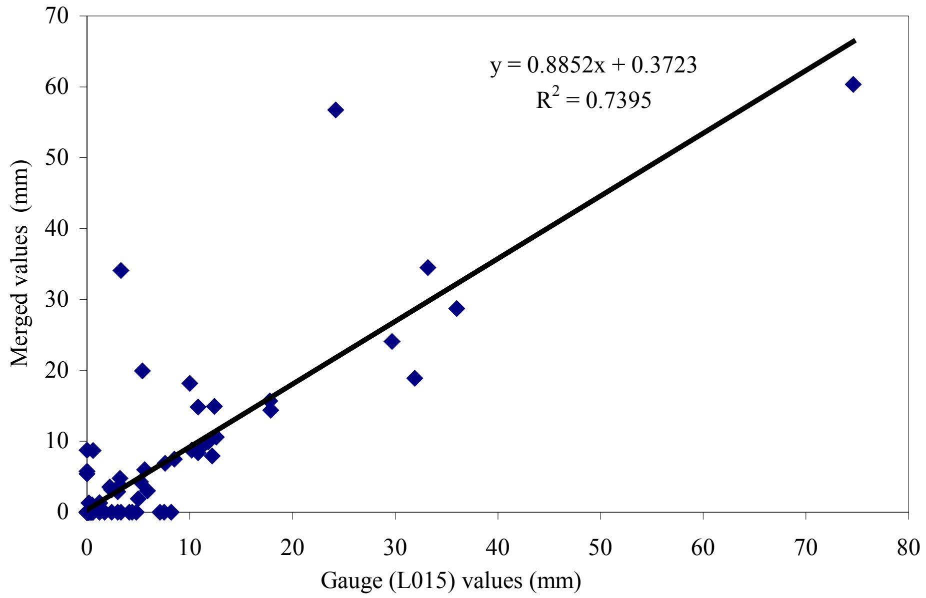

Figure 8 Comparison between merged pixel rainfall at location of daily Raingauge 03312607W and a nearby tipping bucket raingauge (L015).

3.2.3 Estimation of Subcatchment Rainfall from Daily Rainfall

Relationships between the mean merged areal rainfall in the subcatchments of the Liebenbergsvlei catchment, and daily and tipping bucket raingauges selected to represent rainfall in the subcatchments, were developed using data for the period when the merged rainfall values were available. These relationships could then be used to improve the estimation of catchment rainfall using historical data from the selected raingauges.

The downstream part of the Liebenbergsvlei catchment is relatively flat compared to the upstream part of the catchment. As a result the size of the subcatchments delineated by Jewitt *et al*. (1997) are bigger in the downstream portion than in the upstream part. As shown in Figure 1, Subcatchment 26 is situated in the lower portion of the study area and it is a relatively flat area with an area of 827.34 km^2. The location of Station 0367601W is shown in Figure 9. Figure 10 shows the relationship between the average merged rainfall depth for Subcatchment 26, obtained by averaging all the merged rainfall values at each pixel within the subcatchment, and the daily raingauge (W0367601) values. The linear relationship obtained ($y = 0.8157x$; $R^2 = 0.7227$) indicates that the daily raingauge generally overestimates the areal rainfall for the subcatchment. Similar results were obtained for the other catchments.

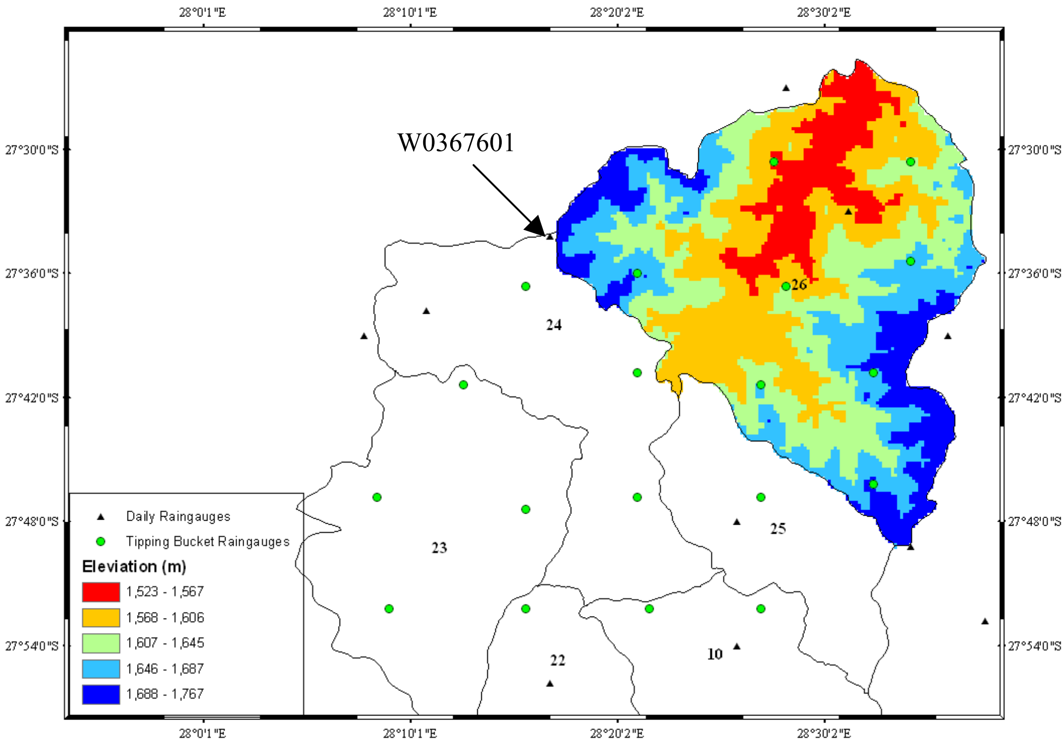

Figure 9 Location of Raingauge 0367601W and altitude map of Subcatchment 26

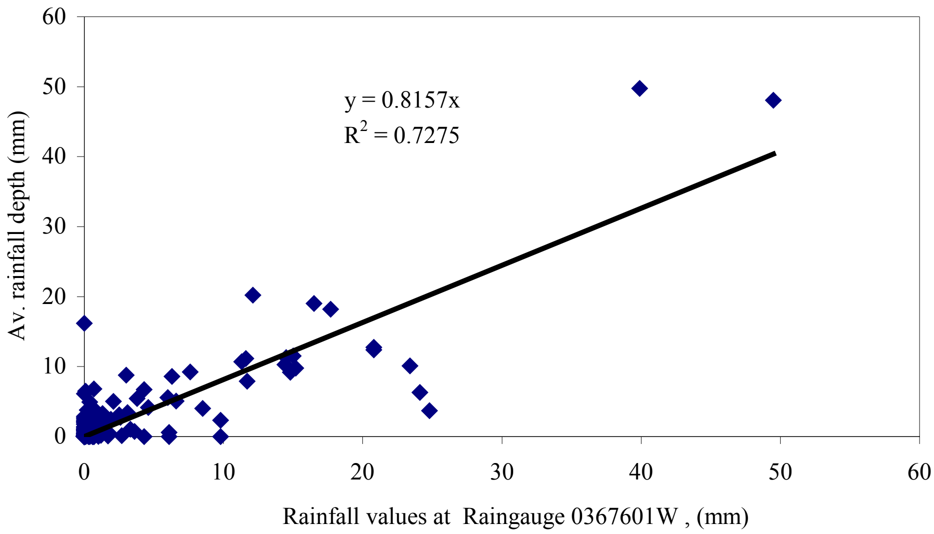

Figure 10 Relationship between average subcatchment rainfall, derived from the merged rainfall field, and rainfall from Raingauge 037601W in Subcatchment 26

The spatial distribution of rainfall within the Subcatchment 26 is relatively uniform for the period shown in Figure 11, where the standard deviation of rainfall on each day over the subcatchment is shown, and where the majority of days have a standard deviation of less than 10 %. The spatial uniformity of the rainfall over the subcatchment implies that there is little or no orographic effect on the spatial distribution of the rainfall. Although the area of Subcatchment 26 is relatively large, the spatial rainfall distribution of the subcatchment is relatively uniform as shown in Figure 11. Therefore, the reason that rainfall at Raingauge 0367601W overestimates the average merged values for Subcatchment 26, could be attributed to either the size of the catchment or the altitude of the raingauge (1672 m), which is higher than most parts of the subcatchment, (average=1645 m).

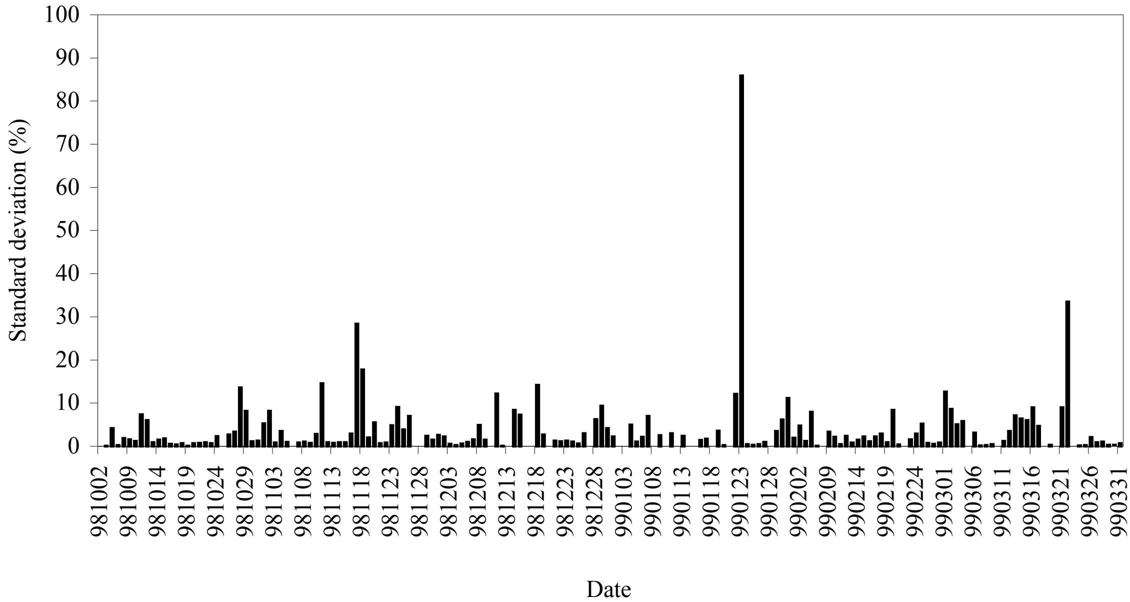

Figure 11 Standard deviation of the spatial distribution of daily rainfall within Subcatchment 26

The correlation between selected daily raingauges and the average merged rainfall depth for the subcatchments in Liebenbergsvlei catchment were found to be generally good, with correlation coefficients greater than 0.5 for most subcatchments. However, in most of the cases the use of a daily raingauge to represent the rainfall for a subcatchment overestimates the average areal rainfall depth of the subcatchment by between 5% and 50%. The relationships obtained are largely dependent on the spatial variation of rainfall over the subcatchments and the location and altitude of the daily raingauges. An ideal perfect relationship $(Y = x; R^2 = 1)$ between the daily raingauges and average rainfall depths of the subcatchments would only be obtained under a condition of perfect spatial uniformity of daily rainfall over the subcatchments.

4 Discussion and Conclusions

Rainfall is highly variable in space and time and the reliable estimation of design floods from rainfall using continuous simulation modelling (CSM) and other hydrological studies require detailed information of the rainfall distribution in both space and time and for a long period of record. Traditional mathematical interpolation techniques have been used to determine the spatial distribution of rainfall over an ungauged area from raingauge networks. However, the rainfall fields from these techniques fall short of describing the "true rainfall fields". Since the introduction of weather radar as a rainfall measuring technique, researchers have been working to develop a meaningful link between the radar estimated and raingauge measured rainfall data. As a result, models have been developed which combine the rainfall fields from the radar and raingauge networks and these rainfall fields represent the highly variable rainfall fields reasonably well.

Merged rainfall fields for the Leibenbergsvlei catchment were generated using an algorithm developed by Scott (2004), which is based on the conditional merging technique of Ehret (2002). In this study, the merging technique was validated against data from tipping bucket raingauges used in conditioning of the radar images. The conditional merging technique is intended to retain the rainfall depths used in the conditioning of the radar images in the merged rainfall field. The results obtained indicated that gauged rainfalls at the conditioning raingauges were not always retained as the merging technique developed by Sinclair (2004) masks the area where the radar did not register any rain, even though raingauges in this area may have reported rainfall. This was done to avoid false rainfall in other parts of the area. When the masked values were removed from the comparison, a nearly perfect relationship was obtained between the conditioning raingauge data and the merged pixel rainfall values located at the conditioning raingauge.

The merging technique was independently verified using daily raingauges which were not used in the conditioning of the radar images. For most subcatchment reasonably good verifications were obtained with X-coefficient ranges between 0.8 to 1.2 and correlation coefficients greater than 0.5. However the relationship depends on the distance between the tipping bucket raingauge used in conditioning of the radar image and the daily raingauge under consideration.

The average merged rainfall values for each subcatchment of the Liebenbergsvlei catchment were related to rainfall from raingauges selected to represent rainfall in the subcachments. The relationships were generally found to be good, with correlation coefficients of greater than 0.5 for most of the subcatchments. However, the raingauges selected to represent the areal rainfall of the subcatchments generally overestimated the mean areal merged rainfall values of the subcatchments by between 5% and 50%. The relationship developed and the the historical rainfall data from the raingauges can be used to provide improved estimates of average catchment rainfall for use in modelling and other hydrological studies. The errors in estimating rainfall for a catchment using a raingauge have been highlighted as a consequence of this study and the need to use the merging process where radar data is available is evident.

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